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# ARAC: A Flexible Real-Time Dose Consequence Assessment System

James S. Ellis and Thomas J. Sullivan
University of California
Lawrence Livermore National Laboratory
Livermore, CA 94551-0099

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# ARAC: a Flexible Real-Time Dose Consequence Assessment System

James S. Ellis and Thomas J. Sullivan
Lawrence Livermore National Laboratory
Livermore, California 94550

## Abstract

Since its beginning, the Atmospheric Release Advisory Capability (ARAC), an emergency radiological dose assessment service of the U.S. Government, has been called on to do consequence assessments for releases into the atmosphere of radionuclides and a variety of other substances. Some of the more noteworthy emergency responses have been for the Three Mile Island and Chernobyl nuclear power reactor accidents, and more recently, for a cloud of gases from a rail-car spill into the Sacramento river of the herbicide metam sodium, smoke from hundreds of burning oil wells in Kuwait, and ash clouds from the eruption of Mt. Pinatubo. The spatial scales of these responses range from local, to regional, to global, and the response periods from hours, to weeks, to months. Because of the variety of requirements of each unique assessment, ARAC has developed and maintains a flexible system of people, computer software and hardware.

## Introduction

Under the auspices of the U.S. Department of Energy (DOE) ARAC's mission evolved to include providing its services to 70 designated facilities within the DOE and U.S. Department of Defense (DOD) communities, in addition to maintaining its ability to respond to radionuclide or other hazardous material releases anywhere in the United States. Federal agencies can request ARAC's services for radiological accidents through the DOE as specified in the U.S. Federal Radiological Emergency Response Plan.

ARAC personnel have participated in a variety of exercises and have assessed actual radiological releases that range from small accidental ventings to the Chernobyl reactor disaster (Sullivan et al. 1993). Each new situation has helped identify areas in which ARAC's emergency response service could be improved. As a consequence, much of ARAC's growth has resulted from "lessons learned" being transformed into new capabilities (Sullivan 1988).

## Responses to Accidents

During the past 18 years, ARAC has responded to more than 60 alerts, accidents, and disasters, and to over 500 exercises. The characteristics of selected past responses are listed in Table 1. In 1976, early in the history of ARAC, a train accident in North Carolina revealed that the availability of real-time meteorological data automatically formatted for use in the dispersion models was essential to a rapid response. In 1978, the unique request by the DOE to estimate the atmospheric consequences of Russian nuclear-powered COSMOS satellites burning up during reentry led the ARAC team to develop a high-altitude, particle-fall model. As a result, in 1981 ARAC was prepared for the reentry of COSMOS 1402. ARAC's largely manual response to the 1979 Three Mile Island accident indicated the need for automated, on-line, U.S. topography and geography databases (Knox et al. 1981). The 1986 Chernobyl accident propelled ARAC to implement continental-to-hemispheric scale models supported by worldwide terrain and mapping data (Sullivan 1991).

In 1991, ARAC experienced an unprecedented demand for its emergency services. The first request came on 16 January 1991, just as Operation Desert Storm began in the Persian Gulf. DOE Headquarters asked ARAC to model the hypothetical dispersal of chemical warfare agents that might be carried on SCUD missiles. This request was closely followed by two others asking ARAC to model the dispersal of radioactive material that might be released from bombed Iraqi nuclear reactors and to prepare realistic evaluations of hypothetical and real oil-fire scenarios that might affect aircraft and weapon system operations. This last effort proved beneficial in the post-war period, when ARAC responded to requests to use its newly developed oil-fire assessment tools to forecast the position of the smoke plume from the fires set by the Iraqis in Kuwait's oil fields. These forecasts continued through 6 November 1991, when the last fire was extinguished. On 14 June 1991, and in the midst of work on the smoke plumes in Kuwait, Mt. Pinatubo in the Philippines erupted. The U.S. Air Force asked ARAC to forecast the locations and concentrations of the ash plumes from this volcano. They used this information to select safe flight corridors through the ash-filled sky, which helped in the evacuation of U.S. citizens from areas endangered by the volcano. Finally, on 15 July 1991, ARAC was asked to model the air concentration of toxic gases resulting from the photodissociation of metam sodium, a herbicide that had spilled from an overturned railroad tank car into California's upper Sacramento River and traveled 80 km to Lake Shasta. The State of California Office of Emergency Services requested ARAC model the concentration of the material released from the lake's surface (but not from the earlier, more severe release along the river).

While meeting these challenges in 1991, ARAC tested the reasonableness of its models and added significantly to the range of problems that it could address. It also proved the reliability of the system, which had been adapted to assess and respond to concurrent, multiple, unrelated events at different locations.

**Transport and Dispersion Codes**

MATHEW (Mass Adjusted Three-Dimensional Wind) and ADPIC (Atmospheric Diffusion Particle-in-Cell) are the primary codes used by ARAC for atmospheric dispersion. MATHEW works with the preprocessing codes TOPOG and MEDIC. Essentially, TOPOG is used to specify the relationship between a three-dimensional grid and a volume above and including the earth's terrain. It maps the terrain data to the nodes or cells of the grid. MEDIC takes a spatially sparse set of horizontal wind data and extrapolates/interpolates it to the nodes above the terrain of the three-dimensional grid. Stability criteria are used to derive the surface layer winds from the surface wind data. A power law with an exponent based on stability is used to adjust all of the surface wind data to a reference height. These adjusted wind data along with upper air horizontal wind data are interpolated to the nodes of the three-dimensional grid.

MATHEW (Sherman, 1978) assumes that the three-dimensional interpolated wind velocities are a fair representation of the actual mean wind field and only need to be minimally adjusted to significantly reduce the remaining divergence and to account for the effects of the terrain on the wind field. The interpolated three-dimensional winds are adjusted in a weighted least-squares sense to satisfy the continuity equation within the atmospheric volume specified. This procedure produces a mass consistent, non-divergent, u, v and w component vector wind field.

ADPIC (Lange, 1978) is a numerical, three dimensional, Cartesian coordinate, particle-diffusion code that calculates the time-dependent distribution of air pollutants under many conditions including strongly distorted wind fields and calm conditions, with wet and dry deposition, radioactive decay, and space-and time-variable diffusion parameters. ADPIC solves the three dimensional advection-diffusion equation in its flux conservative form (pseudo-velocity technique) for a given mass-consistent advection field (supplied by MATHEW) by finite difference approximations in Cartesian coordinates. The method is based on the particle-in-cell technique with pollutant concentration represented statistically by Lagrangian marker particles imbedded in an Eulerian grid. The code has been applied to instantaneous and continuous releases over spatial scales from tens of meters to thousands of kilometers.

ADPIC has been evaluated against many field studies involving neutrally buoyant tracers released both as surface and elevated point sources, as well as material dispersed by explosive, thermally buoyant release mechanisms (Foster and Dickerson, 1990). Results from these studies show that the MATHEW/ADPIC models estimate the tracer air concentrations to within a factor of two of the measured values 20% to 50% of the time, and within a factor of five of the measurements 35% to 85% of the time depending on the complexity of the meteorology and terrain, and the release height of the tracer.

## Staff, Facilities, and Operations

ARAC currently supports a staff of 32 (about half operations staff and half computer scientists), a DEC VAX-based computer system, and 50 remote-site computer systems. For radiological incidents at ARAC-supported facilities, the time to create and deliver plots to the site's computer can be as short as 10 to 15 minutes after the receipt of accident information. For nonradiological incidents, the response time depends on the complexity of the source term, the availability of meteorological data, and the preparation of unique model-input parameters. Typically, ARAC's response time is equally divided among computer (or voice) communications with the site, automated (or manual) model input preparation, model execution, and human interaction with the system.

Figure 1 depicts the ARAC Emergency Response Operating System (AEROS) computer network. Each ARAC-supported facility in the system has a desktop computer for entering initial accident reports. ARAC currently uses 35 million instructions/second (Mips) Digital Equipment Corporation (DEC) VAX 6610 computers to run the models and MicroVAXs to communicate with DEC PC350/380 site computers. Each of the facilities supported by ARAC has one or more meteorological towers that automatically transfer data directly into the on-site computer via modems every 15 min. In late-1993, ARAC will begin replacing the site computers with SUN UNIX-based workstations that communicate with ARAC at 9600 baud and provide site users with a processor 100 times faster than the DEC PCs.

The functionality of AEROS is shown in figure 2. AEROS automatically assembles necessary information for the model run stream once the minimum incident data have been entered into the computer system with the on-line "problem questionnaire." ARAC typically starts the response on a "local" to "regional" scale (10 to 200 km). As the response evolves, the operations staff can expand or contract the model grid proportional to the extent of the hazard. Responses to hazardous atmospheric releases can be initiated in two ways:

- Operations staff at the central ARAC facility can complete the on-line questionnaire using accident information received by telephone from the site or emergency response authorities coupled with defaults from on-line databases.

- Remote-site personnel can enter accident information directly into their site's on-line questionnaire. This information is automatically transmitted to ARAC's central facility from the site computer via a modem.

## ARAC Databases

During an ARAC response, hourly surface and twice-daily upper-air meteorological data are automatically acquired from ARAC's dedicated 9600-baud link to the U.S. Air Force Global Weather Central (AFGWC). In 2 minutes, these data can be received, decoded, and formatted for input to the model. Depending on the situation, meteorological variables, such as atmospheric stability, mixing height, and vertical-wind-power-law profile parameters, can either be determined automatically using on-line algorithms or input manually by the assessment meteorologist who is running the computer codes. A variety of source-term inputs such as release rate, source geometry, particle-size distribution, and deposition velocity are calculated from the questionnaire information and on-line databases.

The geographic databases provide mapping information on scales ranging from buildings and streets on the local scale to country outlines on the hemispherical scale. For general map coverage of the United States, ARAC uses the U.S. Geological Survey (USGS) 1:2,000,000 Digital Line Graph (DLG) database (Walker 1989). ARAC's on-line topographical database is derived from the Defense Mapping Agency's Digital Terrain Elevation Data covering much of the world with 0.5-km resolution and NOAA's ETOPO5 data covering all of the world at 5 minute (~8.0 km) resolution. The dose-factor database contains DOE estimates of dose-conversion factors for internal and external exposure for nuclides of concern. In the future, ARAC plans to add a population database.

**Future Directions**

First to be implemented in late 1993 will be a "hybrid-particle" extension of ADPIC. This improvement will allow ADPIC to model an unlimited number of nuclides and the ingrowth and decay of daughter products. Consequently, sources of mixed fission products, such as those from nuclear reactor accidents, will be treated in their full complexity.

Another new development will be the "predictor-corrector" addition to MATHEW/ADPIC (Edwards et al. 1993), which will automate the integration of model calculations and field measurements. Often, accurate source rate or amount are not known during an accident, but concentration measurements in the field are readily available. The predictor-corrector code performs an automated, nonlinear, least-squares regression analysis to optimize the agreement between a set of paired measured and modeled concentrations. The objective scheme can iterate on several model-input parameters (such as the source rate, the source release geometry, the deposition velocity, or the wind field) within reasonable ranges of uncertainties and find the best fit to the concentration measurements. In real-time accident situations it is the usual case that the greatest uncertainty is associated with the source term information.

In addition, research at LLNL has been directed toward developing state-of-the-art treatments of diffusion using Monte Carlo techniques based on the Langevin equation and random displacement formulations in ADPIC (Rodean et al. 1992). These methods can (a) improve diffusion calculations near sources, (b) use direct measures of atmospheric turbulence, (c) eliminate grid-based numerical errors, and (d) improve diffusion calculations in unstable boundary layers.

In late 1993, ARAC will upgrade its VAX cluster with two 125-Mips VAX 7000-620 computers. This improvement begins to make possible implementing more sophisticated real-time models. Near-future plans include engineering a prognostic, regional-scale emergency-response model, such as the hydrostatic Simulator of the Atmospheric Boundary Layer (SABLE) model (Zhong et al. 1991), into the ARAC system. Prognostic models can simulate and forecast flows dominated by local forcing (e.g., nocturnal drainage flows and sea-breeze circulations). In the future, more powerful computers may allow even more sophisticated, non-hydrostatic meteorological models and dense-gas dispersion models to be used for very complex emergency response problems.

A framework for developing a toxic-chemical emergency-response modeling capability exists at ARAC. Responses to atmospheric releases during major transportation accidents rely on quick access to meteorological data and models to accurately simulate winds where observations are sparse. However, significant new developments with default source terms, release mechanisms, toxic chemical properties databases and exposure indices would have to be added at ARAC to establish a real-time operational capability for responding to releases of toxic chemicals. In addition, new tools such as the dense-gas models developed by Ermak (1992) would need to be engineered into the operational environment. Industrial hygienists and chemists would have to be added to the ARAC operations staff, and training would have to be extended to include the assessment of toxic chemical accidents.

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## References

Edwards, L. L., R. P. Freis, L. G. Peters, P. H. Gudiksen, and S. E. Pitovranov, 1993: The use of nonlinear regression analysis for integrating pollutant concentration measurements with atmospheric dispersion modeling for source term estimation. *Nucl. Technol.*, **101**, 168–180.

Ermak, D. L., 1992: Dense-gas dispersion advection-diffusion model. *Proceedings of the Joint Army-Navy-NASA-Air Force Safety and Environmental Protection Subcommittee Meeting*. Monterey; also Lawrence Livermore National Lab. Rep. UCRL-JC-109697. [Available from National Technical Information Service, U.S. Dept. of Commerce, Springfield, Virginia 21161.]

Foster, K. T., and M. H. Dickerson, 1990: An updated summary of MATHEW/ADPIC model evaluation studies. Presented at the *Workshop on Mechanistic Analyses Involving Aerosols in Non-Reactor Facility Accidents*. Salt Lake City, Amer. Nucl. Soc.; also Lawrence Livermore National Lab. Rep. UCRL-JC-104134. [Available from National Technical Information Service, U.S. Dept. of Commerce, Springfield, Virginia 21161.]

Gudiksen, P. H., T. F. Harvey, and R. Lange, 1989: Chernobyl source term, atmospheric dispersion, and dose estimation. *Health Phys.*, **57**, 697–706.

Knox, J. B., M. H. Dickerson, G. D. Greenly, P. H. Gudiksen, and T. J. Sullivan, 1981: The Atmospheric Release Advisory Capability (ARAC): Its use during and after the Three Mile Island accident. Lawrence Livermore National Lab. Rep. UCRL-85194, 41 pp. [Available from National Technical Information Service, U.S. Dept. of Commerce, Springfield, Virginia 21161.]

Lange, R., 1978: A three-dimensional particle-in-cell model for the dispersal of atmospheric pollutants and its comparison to regional tracer studies. *J. Appl. Meteor.*, **17**, 320–329.

Rodean, H. C., R. Lange, J. S. Nasstrom, and V. P. Gavrilov, 1992: Comparison of two stochastic models of scalar diffusion in turbulent flow. Preprints: *The 10th Symposium on Turbulence and Diffusion*. Portland, Amer. Meteor. Soc., 106–109; also Lawrence Livermore National Lab. Rep. UCRL-JC-110377. [Available from National Technical Information Service, U.S. Dept. of Commerce, Springfield, Virginia 21161.]

Sherman, C. A., 1978: A mass-consistent model for wind fields over complex terrain. *J. Appl. Meteor.*, **17**, 312–319.

Sullivan, T. J., 1988: ARAC: Evolution by accident. *Proceedings of the Topical Meeting on Emergency Response Modeling*, Charleston, Amer. Nucl. Soc., 1–8; also Lawrence Livermore National Lab. Rep. UCRL-98033, Rev. 1. [Available from National Technical Information Service, U.S. Dept. of Commerce, Springfield, Virginia 21161.]

Sullivan, T. J., 1991: ARAC: A computer-based emergency-response dose-assessment service with global application potential. *Proceedings of the Tenth International System Safety Society Conference*, Dallas, 6.1-2-1–6.1-2-16; also Lawrence Livermore National Lab. Rep. UCRL-JC-107201. [Available from National Technical Information Service, U.S. Dept. of Commerce, Springfield, Virginia 21161.]

Sullivan, T.J., J.S. Ellis, C.S. Foster, K.T. Foster, R.L. Baskett, J.S. Nasstrom, W.W. Schalk III, 1993: Atmospheric Release Advisory Capability: Real-time modeling of airborne hazardous materials. Submitted to the *Bull. Amer. Meteor. Soc.* ; also Lawrence Livermore National Lab. Rep. UCRL-JC-111869. [Available from National Technical Information Service, U.S. Dept. of Commerce, Springfield, Virginia 21161.]

Walker, H., 1985: Spatial data requirements for emergency response. *Proceedings of the 1985 Conf. on Emergency Planning*. San Diego, Soc. for Computer Simulation, **15** (1), 82–86; also Lawrence Livermore National Lab. Rep. UCRL-91263. [Available from National Technical Information Service, U.S. Dept. of Commerce, Springfield, Virginia 21161.]

Walker, H., 1989: Use of the 1:2,000,000 digital line graph data in emergency response. *Proceedings of the International Symp. on Cartography and Computing, AUTO CARTO IX*. Amer. Soc. Photogrammetry and Remote Sensing/Amer. Congress on Surveying and Mapping, Baltimore, 472–482; also Lawrence Livermore National Lab. Rep. UCRL-99435. [Available from National Technical Information Service, U.S. Dept. of Commerce, Springfield, Virginia 21161.]

Zhong, S., J. M. Leone, Jr., and E. S. Takle, 1991: Interaction of the sea breeze with a river breeze in an area of complex coastal heating. *Boundary-Layer Meteor.*, **56**, 101–139.

Table 1. Some ARAC responses over the history of the project.

| Year | Location | Source | Release |
|---|---|---|---|
| 1976 | North Carolina | Train accident | Uranium hexafluoride |
| 1978 | Northern Canada | COSMOS 954 reentry | Fission products |
| 1979 | Harrisburg, Pennsylvania | Three Mile Island Nuclear Power Plant | Mixed fission products |
| 1980 | Damascus, Arkansas | Titan II missile | Missile fuel |
| 1981 | Indian Ocean | COSMOS 1402 reentry | Fission products |
| 1982 | South Carolina | Savannah River Plant | Hydrogen sulfide leak |
| 1986 | Gore, Oklahoma | Sequoyah Fuels Plant | Uranium hexafluoride |
| 1986 | Chernobyl, USSR | Nuclear Power Plant | Mixed fission products |
| 1988 | Miamisburg, Ohio | Mound Plant | Tritium gas |
| 1989 | Amarillo, Texas | Pantex Plant | Tritium gas |
| 1991 | [illegible]sian Gulf | Nuclear facilities<br>Kuwait oil fires | Mixed fission products<br>Smoke |
| 1991 | Philippines | Mt. Pinatubo | Volcanic ash |
| 1991 | Northern California | Railroad car spill | Toxic gas products |
| 1992 | Sosnovy Bor, Russia | Nuclear power plant | Radioactive gases |
| 1993 | Richmond, California | Railroad tank car | Sulfur trioxide |

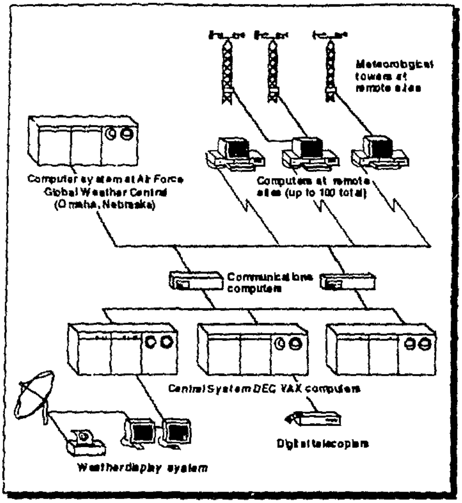


Fig. 1. The ARAC Emergency Response Operating System (AEROS) computer network.

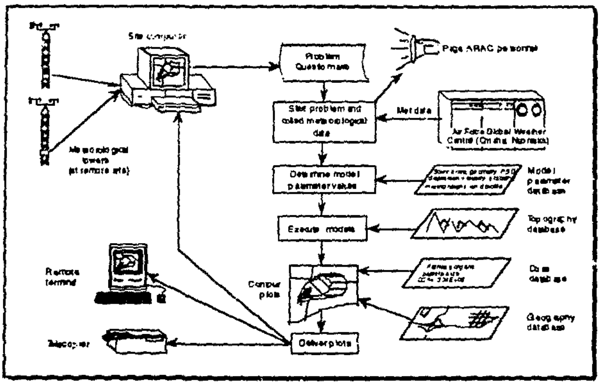


Fig. 2. The primary functions of AEROS.